

Gamma Ray Bursts as Probes of the First Stars

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Abstract. The redshift where the first stars formed is an important and unknown milestone in cosmological structure formation. The evidence linking gamma ray bursts (GRBs) with star formation activity implies that the first GRBs occurred shortly after the first stars formed. Gamma ray bursts and their afterglows may thus offer a unique probe of this epoch, because they are bright from gamma ray to radio wavelengths and should be observable to very high redshift. Indeed, our ongoing near-IR followup programs already have the potential to detect bursts at redshift $z \sim 10$. In these proceedings, we discuss two distinct ways of using GRBs to probe the earliest star formation. First, direct GRB counts may be used as a proxy for star formation rate measurements. Second, high energy cutoffs in the GeV spectra of gamma ray bursts due to pair production with high redshift optical and ultraviolet background photons contain information on early star formation history. The second method is observationally more demanding, but also more rewarding, because each observed pair creation cutoff in a high redshift GRB spectrum will tell us about the integrated star formation history prior to the GRB redshift.

INTRODUCTION

The high redshift frontier of observational cosmology currently stands at redshifts $z \approx 6$. The current redshift record is a quasar at $z = 5.8$, and a few galaxies are known at marginally lower redshift. Beyond $z = 6$, we have yet to identify any individual objects. We do know that hydrogen was predominantly neutral at redshifts $z \gtrsim 30$ based on the observed anisotropy of the cosmic microwave background, which would be smoothed out by Thomson scattering if the free electron density at $z \gtrsim 30$ were too great. The redshift range $6 \lesssim z \lesssim 30$ remains unknown territory. It is a very interesting territory, too, for it should include the formation of the first stars, galaxies, and quasars, and certainly includes the epoch at which hydrogen was reionized.

Searches for starlight (and other rest-frame near ultraviolet tracers) can make incremental progress into the low-redshift end of this period. However, these methods face a practical limit where the Lyman break redshifts out of the optical window to the near-infrared, at $z \approx 7$. At higher redshift, essentially no flux is expected in the optical window (observed wavelengths $0.36\mu\text{m} \lesssim \lambda_{\text{obs}} \lesssim 1\mu\text{m}$). Atmospheric conditions and present detector technologies conspire to make searches at $\lambda_{\text{obs}} \gtrsim 1\mu\text{m}$ much less efficient. Future instrumentation like the Next Generation Space Telescope (NGST) promise extensions of “conventional” optical methods to the observed near-IR and thus to redshifts $z \gg 6$, but this may be a decade or more away. In the meantime, we expect the upcoming extension of our Large Area Lyman Alpha (LALA) survey (Rhoads et al 2000; Malhotra et al 2001) to $z = 6.6$ to be at or near the practical limit for some years.

We would like to find tracers of $z > 6$ objects that are accessible now. Fortunately, this is possible so long as we are willing to use something besides starlight. In practice,

this means higher energy photons (γ and x-rays), since lower energies still face either confusion or sensitivity issues.

Gamma ray bursts (GRBs) are an excellent candidate for detection at high redshift because the bursts and their afterglows are extremely bright at all wavelengths. Two conditions must be met for such a candidate to work well. First, there should be a reasonable expectation that the object exists at high redshift; and second, it should be detectable there.

The best argument that gamma ray bursts should occur at high redshift comes from the growing body of evidence linking GRBs to star formation activity (and hence presumably to the deaths of massive, short-lived stars): GRB host galaxy colors are characteristically blue (Fruchter et al 1999); the spatial distribution of GRBs on their hosts matches expectations for hypernova models (Bloom, Kulkarni, & Djorgovski 2000); and the emission lines of GRB host galaxies are unusually strong (Fruchter et al 2001). Structure formation models yield estimated redshifts $z \sim 15 \pm 5$ for the first stars to form in the universe (cf. Barkana & Loeb 2001). This is supported by studies of heavy element abundances: It has proven extremely difficult to find objects with primordial (i.e., big bang nucleosynthesis) abundances at any redshift currently accessible. The immediate inference is that a substantial generation of stars must have existed at earlier redshifts to produce the ubiquitous metals. The association of GRBs with star formation then implies that the first GRBs also occurred in the redshift range $z \sim 15 \pm 5$.

The detectability of GRBs at $z \gg 6$ has been considered in detail by Lamb & Reichart (2000), who find that the bright end of the luminosity distribution would be detectable at very high redshifts (though quantitative predictions depend substantially on unknown details of the GRB luminosity function). This applies also to the X-ray and optical afterglows, for which time dilation of the most distant afterglows helps offset the increase in luminosity distance with redshift (Lamb & Reichart 2000; Ciardi & Loeb 2000).

The Lyman break will render afterglows at $z > 7$ invisible to optical detectors, just as it does for galaxies. But the problem here is not so serious. Searches for $z > 7$ galaxies suffer because galaxies at such high redshifts are faint, and the required combination of large solid angles and high sensitivity to find them is not yet practical at near-IR wavelengths. Because GRB afterglows outshine their host galaxies at early times, and because X-ray detectors can determine GRB locations with accuracy comparable to the current near-IR field of a 4m class telescope, an afterglow at this redshift is easier to find than are the galaxies around it. Indeed, published near-infrared afterglow observations (Rhoads & Fruchter 2001) already achieve a sensitivity sufficient to detect afterglows at $z \sim 10$ for several hours following a GRB (cf. figures 2,3 of Lamb & Reichart 2000). The followup program described in Rhoads & Fruchter 2001 is continuing at the NASA Infrared Telescope Facility, and we have a similar program at the National Optical Astronomy Observatory. The observed signature of a $z > 7$ GRB would be a near-infrared afterglow exhibiting a Lyman break at $\lambda_{obs} = 0.1215(1+z)\mu m > 1\mu m$. Such breaks have been used to measure $z = 2.05$ for GRB 000301C (Smette et al 2001) and to estimate $z \approx 5$ for GRB 980329 (Fruchter 1999; see also Reichart et al 1999). Their extension to longer wavelengths is straightforward. Thus, it is reasonable to expect that $z > 7$ GRBs will be detected with current technology.

The prospect of detecting gamma ray bursts at $z > 7$ opens two possible methods of studying star formation activity at these epochs: GRB rate evolution, which should trace

star formation activity; and pair production cutoffs in the GeV spectra of bursts, which probe the total optical-ultraviolet background light produced by high redshift stars.

BURST RATE EVOLUTION

The most basic inference from the observed burst rate is that the highest redshift where a burst has been detected $z_{max,grb}$ implies the onset of star formation at some redshift $z_{max,*} > z_{max,grb}$. It is likely that in fact $z_{max,*} \approx z_{max,grb}$. The association of GRBs with star formation tracers requires short progenitor lifetimes ($\ll 10^8$ years), so the redshift difference between the first stars formed and the earliest possible hypernovae is small.

It will be possible to go further by measuring the GRB rate as a function of redshift, $R_{grb}(z)$, and taking it as a surrogate for the star formation rate. Such studies would require a large sample (several tens) of high redshift GRBs, together with an understanding of the selection effects that went into the sample. This method is likely to be limited by at least two systematic factors. First, uncertainties in the GRB luminosity function will introduce uncertain corrections to the inferred total GRB rate and the inferred star formation rate, since the high redshift sample will contain only bright bursts. Second, evolution in the burst progenitor population may influence the burst rate. One plausible example is that the GRB rate could depend on progenitor metallicity, which is likely to be lower in the early universe. Another is that the stellar initial mass function (IMF) may vary, thereby affecting the relation between GRB rate and star formation rate, and perhaps also the shape of the GRB luminosity function. Possible evidence for IMF variations has recently been found in at some high redshift Lyman α emitting galaxies (Malhotra et al 2001).

Overall, these complications suggest that calibration of the GRB rate as an indicator of global star formation might be possible to within a factor of a few. While higher accuracies would be desirable, the present uncertainties with more conventional star formation estimators are not much better. For example, rest ultraviolet continuum measurements are corrected by a factor of ~ 7 for dust absorption, and the uncertainty in this correction could easily be a factor of two given the range of possible dust properties.

PAIR PRODUCTION CUTOFFS IN GRB SPECTRA

The observed spectra of gamma ray bursts sometimes extend to very high photon energies: The EGRET experiment on the Compton Gamma Ray Observatory detected four bursts with unbroken power law tails extending to $\mathcal{E}_\gamma > 1\text{GeV}$, and the Milagrito air shower experiment has tentatively detected one burst at $\mathcal{E}_\gamma \gtrsim 1\text{TeV}$. Photons with such high energies have mean free paths shorter than a Hubble distance due to $\gamma + \gamma \rightarrow e^+ + e^-$ interactions with low energy background photons. The threshold for such pair production reactions is $\mathcal{E}_\gamma \epsilon_\gamma > m_e^2 c^4 = (511\text{keV})^2$, corresponding to the requirement that each photon have the rest mass energy of an electron in their center of momentum frame. (Here \mathcal{E}_γ and ϵ_γ are the two photon energies measured in an arbitrary frame, and $\mathcal{E}_\gamma \geq \epsilon_\gamma$ by convention.) The cross section (for a head-on collision) peaks at $\mathcal{E}_\gamma \epsilon_\gamma = 2m_e^2 c^4$ and

falls asymptotically as $1/(\mathcal{E}_\gamma \epsilon_\gamma)$ for $\mathcal{E}_\gamma \epsilon_\gamma \gg 2m_e^2 c^4$.

Pair production cutoffs in the TeV gamma ray spectra of blazars due to interactions with the cosmic infrared background have been predicted (Stecker, De Jager, & Salamon 1992; MacMinn & Primack 1996; Madau & Phinney 1996; Malkan & Stecker 1998) and observed (e.g., De Jager, Stecker, & Salamon 1994; Konopelko et al 1999) for several years now. The extension of the same physics to higher redshifts and lower gamma ray energies has been explored recently by several groups (Salamon & Stecker 1998; Primack et al 2000; Oh 2000).

The observer frame gamma ray energy determines simultaneously the redshift and rest frame energies of the background photons that dominate the pair production optical depth. At low redshifts ($z \ll 1$), the effective absorption coefficient $\alpha(\mathcal{E}_\gamma)$ increases with \mathcal{E}_γ and changes relatively little with redshift, so that the relevant physics is simply $\alpha(\mathcal{E}_{cut})d = 1$, with d the distance to the source. However, at $z \gtrsim 1$, redshift effects become important: The threshold energy $\epsilon_\gamma(z) \propto 1/(1+z)$, and the background radiation field will also evolve with redshift. The optical depth for photons near \mathcal{E}_{cut} is therefore dominated by absorption at high redshift, unless the source redshift is so high as to precede the creation of any substantial optical-IR background. By the time the photon reaches lower redshifts, the threshold for pair creation grows so large that the density of relevant photons is extremely low. Oh (2000) has shown that the highest energy background photons capable of producing optical depth $\tau \approx 1$ over a Hubble distance have energies below the ionization threshold for hydrogen (i.e., $\epsilon_\gamma < 13.6\text{eV}$), since hydrogen absorption in stellar atmospheres, galaxies, and the intergalactic medium ensures a strong decrement in background photon number density at 13.6eV.

The most robust observable consequence of the pair creation cutoff is the observer frame gamma ray energy $\mathcal{E}_{cut}(z)$ for which the optical depth $\tau = 1$. Lower pair creation optical depths ($\tau \ll 1$) cannot be measured reliably because of our imperfect knowledge of the intrinsic (i.e., unabsorbed) source spectrum, while at higher optical depths ($\tau \gg 1$) the absorption reduces the flux below detection thresholds of present or near-future instruments. We might measure $\tau(\mathcal{E}_\gamma)$ with reasonable accuracy over the range $1/2 \lesssim \tau \lesssim 2$.

Detailed predictions of $\mathcal{E}_{cut}(z)$ differ from model to model, depending on the theoretical treatment adopted for the earliest star formation (see Primack et al 2000; Oh 2000). For example, the observer frame energy where $\tau = 1$ for redshift $z = 6$ is $4\text{GeV} \lesssim \mathcal{E}_{cut}(6) \lesssim 6\text{GeV}$ for different models in Primack et al (2000), and $10\text{GeV} \lesssim \mathcal{E}_{cut}(6) \lesssim 26\text{GeV}$ for models in Oh (2000). Therein lies the power of this method for learning about the first generations of stars, for these strong differences in predictions allow the models to be distinguished with comparative ease from even a modest data set.

Moreover, if we can observe the GeV cutoffs in spectra of a few GRBs spread over the redshift range $6 \lesssim z < z_{max,*}$, we can infer the evolution of the optical-UV background radiation over the same period with little dependence on models. This follows because the *difference* in pair creation optical depth between two bursts at redshifts z_1 and z_2 ($z_1 < z_2$) is determined only by the background radiation in the range $z_1 < z < z_2$.

DISCUSSION

The two methods of using gamma ray bursts to probe high redshift star formation complement each other in many ways. GRB rate measurements at high redshift are technically easier. They require a GRB monitor plus rapid multiband near-infrared followup. Existing instrumentation and indeed existing observational programs are already adequate for this work. Pair creation cutoffs require one additional observation, namely, a GeV energy spectrum obtained during the GRB. This GeV spectrum will have to come from GLAST or a similar space mission.

The physical assumption behind the GRB rate evolution method is that the bursts are associated with star formation activity. Under this assumption, there will be some systematic uncertainties in converting the GRB rate to the star formation rate (see above). In contrast, the pair creation cutoff method requires only that some high redshift GRBs have GeV spectra that are sufficiently bright and sufficiently smooth for the cutoff to be observed. Beyond this, there is no requirement on the nature of the bursters, which are needed only as beacons to probe the intervening background radiation. The physics of pair creation is then well understood and probes the total background radiation produced by high redshift stars.

Thus, combining the two methods of studying high redshift star formation with GRBs may overcome the physical uncertainties of either method alone. Additional constraints from other techniques using other classes of objects (galaxies observed at infrared wavelengths, or quasars at X-ray wavelengths) will become available over the next few years, and will again have complementary strengths and weaknesses. By adding these to the GRB results, we can reasonably expect to understand star formation at $z \sim 10$ as well as we understand it at $z \sim 3$ today.

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